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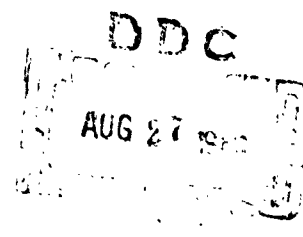
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TECHNIQUES FOR EVALUATING OPERATOR LOADING IN MAN-MACHINE SYSTEMS

Modification and Further Evaluation of a Digital Man-Machine Simulation Model

DDC

AUG 27

Applied Psychological Services

Wayne, Pennsylvania

NO. OTS

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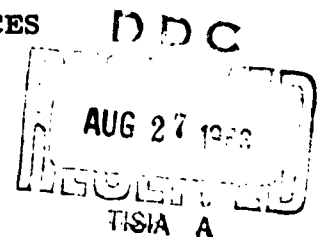
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ABSTRACT

A digital computer simulation model was previously derived and employed for simulating the performance of the operator(s) in a man-machine system. The technique is based on an analysis of the performance of each operator, arranged into ordered, discrete actions called "subtasks," and the compilation for each of certain source data. These data, together with selected parameter values (e.g., the time allotted for task performance) are placed in punched card form and introduced into a digital computer which sequentially simulates, according to the rules of the model, the "performance" of each subtask by each operator. The normal sequence of subtasks may be modified if actions have to be skipped or repeated due to failure of a subtask by either operator or as a result of operator decisions. A simulation is completed when the operators either use all allotted time or successfully complete the task. Results are recorded indicating the areas of operator overload, failure, idle time, peak stress, etc., for the given set of selected parameters. Repetitions of the simulation, with different parameter values, yield a range of records. Frequency distributions, summarized, and reduced data are provided automatically by the computer, and from these, graphs and charts of performance may be prepared.

Since the development of the original model, a number of possible modifications have become apparent. These modifications involve: (1) a newly developed and modified stress formulation, (2) a random interrupt feature,

(3) an alternate method for calculating subtask execution time, (4) changes to incorporate the individuality factor in the urgency and stress calculations, (5) an "equipment delay" simulation feature, and (6) imposition of an upper limit of the stress on the simulated operator.

Moreover, although logical expectancy indicated the model to be usable for either one or two operator systems, the model had never been exercised on a uni-operator system. Accordingly, the present study focused on investigating: (1) the applicability of the model to uni-operator situations, and (2) the effects of the modifications on the agreement of the results from application of the model with criterion data.

The results suggested that the model is usable for uni-operator and for two-operator simulations. The modified model, which demonstrated general reasonableness and rationality, also achieved an agreement level with outside criterion data that had not been previously accomplished.

ACKNOWLEDGMENTS

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CHAPTER I

INTRODUCTION

Background

For several years, Applied Psychological Services, under Office of Naval Research sponsorship, has been engaged in the development and evaluation of digital computer techniques for the simulation and prediction of operator performance in man-machine systems. The initial efforts resulted in the development of a model for a single operator-machine system in which an operator's task performance is simulated.

This uni-operator man-machine system model was formulated for the IBM 650 digital computer using the SOAP programming technique. The tasks of landing an F4D aircraft on an aircraft carrier and launching the Sparrow III air-to-air missile were simulated by the computer and reported (Siegel and Wolf, 1959a, 1959b). This one-man model incorporated provisions for variations of operator speed, task time allowance, operator idle time, stress breakpoint, ignoring of non-essential subtasks when the operator is under time stress, operator decisions, and equipment failures.

Then, the model was generalized and expanded to accommodate systems manned by one or two operators. The team model was organized for the IBM 705 III computer using the AUTOCODER programming technique. In addition to the features of the one-operator model, the expanded version also provided for operator communication, calculation of team "cohesiveness," and waiting

for the partner. Additionally, the computer was programmed to perform a greater amount of the tabulation, summarization, and other processing of the results previously manually performed.

This team model was first applied to the task of in-flight refueling of an F8U aircraft from an A4D tanker (Siegel, Wolf, and Crain, 1961). A second application of the expanded model was made to the task of intercepting an intruding aircraft by an advanced, supersonic naval aircraft manned by a pilot-radar observer team (Siegel and Wolf, 1961). In connection with this second application, the model was modified to incorporate a revised value of time to simulate skipping a non-essential subtask.

Most recently (Siegel, Wolf, and Sorenson, 1962), the two-man model was again expanded and the results obtained from application of the model were compared with the results achieved in a controlled two-operator task. Two sets of electric trains, each under control of a carefully selected operator subject were used to enact a military task in which perceptual-motor behavior, interoperator communication, cooperative action, branching, selection of strategy, and skipping of non-essential subtasks were included. This (Siegel, Wolf, and Sorenson, 1962) study also reported a number of additional changes in the model: (1) providing for the case in which one operator makes a "team" decision for both himself and his partner, (2) providing for the actions of one operator to be dependent on whether his partner performed or skipped a given subtask, and (3) providing for an operator to skip a group of subtasks as well as individual subtasks under certain circumstances.

The Current Study

As a result of the laboratory data, added experience in evaluating computer data, and a need to expand still further the range of usefulness of the simulation method, several additional modifications have been made to the model. A descriptive compilation of the model in its current status is given in the next chapter of the present report. A review of the current operational aspects of the computer program, operator instructions, card and tabulation format, and the like are given in Chapter III.

Since some of these modifications were made on an exploratory basis, several computer simulation runs were made to determine the effects of the changes in the model. In selecting a task on which the changes could be evaluated several criteria were considered. In addition to selecting a task which exercised the various features of the model, there had been for some time the question of how well the two-operator model would perform in the case of a single operator task. The selection therefore was to simulate first the uni-operator controlled launching of a Sparrow III air-to-air missile as previously reported (Siegel and Wolf, 1959b) prior to any changes in the model. Following this, the desired changes were incorporated into the logic of the computer program and the simulations rerun to study the effects of the changes. Chapter IV contains the results of both sets of these computational runs.

CHAPTER II

THE REVISED MODEL

Input Data

The following is a description of the current stochastic model for simulating one or two-operator systems. To use the model, 14 items of input data are required for each subtask (i = 1, 2, ..., n), and each operator (j = 1, 2). These data may be derived from such procedures as task analysis, literature search, or personal interviews. The required input data for each operator are:

1. **average subtask execution time**, $\bar{t}_{ij}$: the average time required by the jth operator to perform subtask i. This average value represents the case in which the operator is under no stress. Examples of values suggested from ·various sources as tentatively applicable for representative subtasks are shown in Table 1.

2. **average standard deviation**, $\bar{\sigma}_{ij}$: taken around the $\bar{t}_{ij}$ for the average operator while not under stress. Examples of values for these data are also shown in Table 1.

3. **average subtask probability of success**, $\bar{p}_{ij}$: the probability that the average operator, j, while not under stress, can perform subtask i successfully.

4. **indication of subtask essentially**, E_{ij}: an indicator specifying whether or not the successful performance of subtask i by operator j is essential to successful completion of the task. This datum allows the computer to identify and ignore non-essential subtasks during "highly urgent" conditions.

5. **idle time requirement**, I_{ij}: the point in time before which operator j is not permitted to begin subtask i.

6. indication of whether subtask i is a **decision subtask** or a **normal action subtask**. A decision subtask is a subtask in

which the computer simulates a choice or decision made by the operator, without, however, the operator taking any action.

7. subtask number, $(i,j)_f$: to be performed next by operator j if he fails at subtask i, or if he chooses the first of two alternative courses in a decision subtask.

8. subtask number, $(i,j)_s$: to be performed next by operator j if he succeeds on subtask i, or chooses the second alternative course in a decision subtask.

9. subtask number, d_{ij} (mnemonic delay): which must be successfully completed by his partner before operator j can begin subtask i. By proper selection of d_{ij} values, it is possible to cause either operator to "wait" until his partner has completed a stipulated subtask successfully. Thus, "waiting" for one's partner is simulated differently from time spent "idling" until a fixed time as in 5 above.

10. indication of whether or not subtask i for operator j is a special subtask in which the operators communicate with each other.

11. time, T_{ij}^E : required to perform all remaining essential subtasks (including i) at average execution times, assuming no failure. With no branching or decisions:

$$T_{ij}^E = \sum_{k=i}^{n} \bar{t}_{kj}$$

12. time, T_{ij}^N: required to perform all remaining non-essential subtasks (including i) at average execution times, assuming no failures.

13. indication of a special type of subtask:

   a. a joint or team decision
   b. a subtask to be skipped by j if a specified subtask is ignored by j'
   c. an equipment delay subtask

14. special $(i,j)_f$ and $(i,j)_s$, like 7 and 8 above for use on special subtasks.

Table 1

Examples of Average Execution Times and Standard Deviations
for Representative Operator Actions*

Operator Action	Average Execution Time $\bar{t}_{ij}$ (sec.)	Average Standard Deviation $\bar{\sigma}_{ij}$ (sec.)
Set Toggle Switch	1.1	0.76
Set Rotary Control	8.6	3.00
Push Button (or foot switch)	4.2	1.02
Lever (throttle) Setting	3.0	0.48
Joystick Setting	3.8	0.48
Read Instrument, N Instruments	0.6N + 0.6	0.2N + 0.2
Communication, N Words	0.66N + 0.6	0.34N + 0.4
Ignore Non-essential subtask when situation is "highly urgent"	0.6	-

* Each t_{ij} value includes 0.6 sec. to allow for attention shift between subtasks, and similarly each σ_{ij} includes 0.2 sec. Data given are for field conditions. In highly controlled laboratory situations, these data should be reduced by 50%.

Parameters and Initial Conditions

The other data required by the computer in advance of the simulation are the parameters and initial conditions. These permit the adjustment of critical variables and the consequent determination of the range of their effects. In order to simulate intra- and inter-individual differences of performance, the simulation of any individual subtask is based, in part, on a random process. Because of this stochastic effect, it is necessary to repeat the simulation of a task many times in order to obtain sufficient performance data for each set of conditions. The parameter N is used to indicate the <u>number of times a given</u>

task is to be simulated; there are N simulations (or N iterations) per computer "run."

Another initial condition is R_0, the nine digit number from which the computer generates subsequent pseudo-random numbers R_1, R_2, R_3,..., needed during the course of the simulation. The term "pseudo-random" is used because the last number generated in one run is used as the first value in the next run and thus any random number generated is not wholly independent of the last. The distributions of pseudo-random numbers as generated are indistinguishable by reasonable statistical tests from numbers which result from a truly random or stochastic process.

Three pairs of parameters may be varied from run to run in order to evaluate either the model or a man-machine system. The stress thresholds, M_j, one for each operator, may be considered as the operator's "breaking point." For example, an M_j value of 2.0 indicates that the operator begins to become slower and less accurate at the point at which he has more than twice as much to do (at average speed) as he has time available. Prior to this point, any added backlog of essential subtasks induces stress which affects the operator's actions so that they become faster and more accurate.

The parameters, T_j, are the total times allotted to each operator for performance of the whole task. For a two-man team, the task is considered to have been successfully completed if both operators complete all required subtasks within the time specified by the larger of the two values.

The parameters, F_j, which account for variance among individuals, are termed the <u>individuality factors</u> for the two operators. F_j is a multiplicative factor with a value of unity for the average operator. For faster or more highly motivated operators ($F_j < 1$), and for slower operators ($F_j > 1$).

The Random Interrupt Feature

Four additional initial conditions are associated with a new feature which provides for the simulation of an event which interrupts a team during its task performance. This feature enables simulation of tasks during which an unexpected event occurs to interrupt one or both operators. It is assumed that the one such interrupt which is permitted in each task simulation will occur at any time between the beginning of the task and T^I seconds later with equal probability. The interrupt occurs on a given simulation with probability P^I and, if it occurs, the interrupt will have a duration which is normally distribule around $\overline{t}^I$ seconds with a standard deviation of $\overline{\sigma}^I$ seconds.

The Simulation Sequence

Having stored the program parameters, and initial conditions, the computer begins processing the data in accordance with the logic shown in Figure 1. To determine whether or not an interrupt is to occur on the forthcoming simulation a pseudo-random number, R_1, uniformly distributed over the unit interval is generated, using the power residue method, from R_0. The interrupt will occur if P^I is less than R_1. In the event that an interrupt is to occur, the duration of the interrupt is calculated as:

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Figure 1 Flow chart of man-machine simulation model

(Figure 1 continuation)

(Figure 1 continuation)

(Figure 1 continuation)

$$D^I = \bar{t}^I + K\bar{\sigma}^I > 0$$

$$\text{where } K = (-2\ln R_2)^{1/2} \cos 2\pi R_3 \quad \text{or}$$

$$(-2\ln R_2)^{1/2} \sin 2\pi R_3, \text{ alternatively.}$$

Since K is calculated to be a random deviate, the interrupt duration will be normally distributed around the mean $\bar{t}^I$ with standard deviation $\bar{\sigma}^I$. The time at which the interrupt will occur is: $T^0 = T^I \cdot R_4$, i.e., equally probable at any time from the beginning to the time T^I.

The computer determines the sequence of subtasks to perform in accordance with $(i,j)_s$ and $(i,j)_f$ input data. Its determination of which operator to simulate at any given time in the sequence depends upon T_{ij}^U, the total time used by operator j while "performing" all subtasks from the start of the simulation through subtask i-1. The operator having the smaller T_{ij}^U value is selected, and his next subtask is simulated. Subtasks are simulated in turn until the task is completed or until all time allotted has been used.

Decision Subtasks

An operator may find it desirable, or external conditions may require him to skip one or more subtasks or, having reached a critical point, to select one of several alternative courses of action. The decision subtask, incorporated to enable such branching, skipping and looping, causes the computer to select the next subtask without "consuming operator time." Decision subtasks may

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be placed anywhere in the sequence. For these, $\bar{t}_{ij}$, $\bar{\sigma}_{ij}$, and essentiality have no meaning. The calculation of execution time is bypassed and the last pseudo-random number, R_3, from the previous subtask is compared against the $\bar{p}_{ij}$ of the decision subtask. Therefore, the next subtask to be performed as a result of the decision, is subtask $(i,j)_s$ with probability $\bar{p}_{ij}$, or subtask $(i,j)_f$ with probability $1 - \bar{p}_{ij}$.

Waiting and Idling

If one operator must wait for another, the sequence continues using data for the other operator. Then a determination is made as to whether the operator must idle until an amount of time I_{ij} has elapsed from the beginning of the simulation. If idling is required, the idle time $I_{ij} - T_{ij}^U$ is recorded, totals accumulated, T_{ij}^U set equal to I_{ij}, and the control returned to determine which operator to simulate next. If no idling is required, a determination is made of whether or not subtask i is a communication subtask. If it is, the operators are synchronized by setting the total time used by both to that of the one who has taken longer. This may result in a wait for either operator and is treated as the wait described above.

Equipment Delays

Before computing each operator's stress and urgency conditions, the computer determines whether the subtask being simulated is an equipment delay subtask. This type of subtask, which can appear wherever desired in

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the subtask sequence, provides for the case in which a delay is introduced and time is used due to factors other than operator performance. The technique for determining the time used in this case is similar to the calculation of subtask execution time discussed later--but without the effects of operator stress involved. The time is calculated from a normal distribution with mean $\bar{t}_{ij}$ and standard deviation $\bar{\sigma}_{ij}$.

Urgency and Stress

For other types of subtasks, one of three states of "urgency" is determined for each operator. Urgency is based on the remaining time available to an operator for completing the task, the average time required to complete the task if no failures occur, and the operator's individuality factor:

1. The situation is non-urgent when sufficient time remains to complete all remaining subtasks.

2. The urgent state occurs if the time available is insufficient for completing all remaining subtasks, but sufficient to complete all remaining essential subtasks.

3. The situation is highly urgent if there is insufficient time available for completing even the remaining essential subtasks.

In the urgent and highly urgent conditions the computer ignores the non-essential subtasks.

Following the determination of the degree of "urgency," the stress condition is calculated. Current psychological theory suggests that emotion or stress acts as an organizing agent on behavior up to a certain point, and beyond it as a

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disorganizing agent.   Accordingly, the model recognizes an organizing effect

on operator performance as long as s_{ij} (the stress upon operator j just prior

to his performance of subtask i) is less than a threshold value M_j: if s_{ij} equals

or exceeds M_j, the effect is disorganizing.   During non-urgent and urgent con-

ditions s_{ij} is defined as equal to unity; when the situation is highly urgent,

stress is defined as the ratio of the sum of the average execution times for the

remaining essential subtasks to the total time remaining:

$$s_{ij} = \frac{\overline{T}^E_{ij}}{T_j - T^U_{ij}} \qquad 1.0 \leq s_{ij} \leq 5.0$$

In other words, stress is the ratio of how much is left to do, to the amount of

time available in which to do it.

Since each operator has an individual time limit on his performance and

a task failure occurs only when the larger of these limits is exceeded, it is pos-

sible for the simulation to continue with one operator (arbitrarily selected as

operator 1) having exceeded his limit.   Should this be the case, the stress con-

dition of this operator is set equal to his threshold value, M_j, for the remainder

of the simulation.

Team Cohesiveness

The model attempts to simulate the operator's confidence in or co-hesiveness with his partner. Lack of team cohesiveness may reflect disagree-ments about goals or their importance, or about methods, or locus of authority. An operator can often tell how well his partner is performing: when one oper-ator "feels" that his partner is not performing satisfactorily, he will probably modify his own actions. The model provides for this contingency by adding to the stress value for one operator if his partner has a stress value greater than unity. The additive, A, is calculated as follows:

$$A = \begin{cases} 0 & \text{if } s_{ij'} = 1 \\[2em] \dfrac{s_{ij'} - 1}{M_{j'} - 1} & \text{if } 1 < s_{ij'} \leq M_{j'} \\[2em] 1 & \text{if } s_{ij'} > M_{j'} \end{cases}$$

where j' denotes the partner. The value $A + s_{ij} = S_{ij}$ is used in later calcu-lations of subtask performance time.

An <u>index of cohesiveness</u>, C_{ij}, is also calculated for each operator on each subtask as a measure of the joint stress condition of the team. It is the product of the stress levels of the two operators normalized by their respective

stress threshold values:

$$C_{ij} = \frac{(s_{ij} s_{ij'}) - 1}{(M_j M_{j'}) - 1}$$

When neither operator is under stress, $C_{ij} = 0$. If the stress on both operators is equal to their thresholds, $C_{ij} = 1$. Thus, increasing C_{ij} values indicate greater team discontinuity.

Subtask Execution Time

Next, the execution time of the subtask is computed. The average operator will require t_{ij} seconds to perform subtask i when $S_{ij} = 1$. In this case, his average standard deviation will be $\bar{\sigma}_{ij}$. Of course, no two operators would be expected to perform any subtask in exactly the same time on each repetition, and no operator would be expected to perform the same task identically on two occasions except by chance. For each subtask, it is assumed that the actual subtask execution time, t_{ij}, is normally distributed. The current model provides two alternative schemes of computing the execution time. The desired function can be selected by appropriate computer switch setting prior to simulation. In both cases, specific values for t_{ij} are selected by a random or Monte Carlo technique from a normal distribution limited from below by a fixed minimum, selected as 0.75 sec. Pseudo-random numbers R_1 and R_2 uniformly distributed in the unit interval are sequentially generated by the computer from R_0 as before. From these numbers, corresponding values of an independent random, normally distributed variable are generated. Thus, if K_{ij} is the number of standard deviations from the mean corresponding to the random numbers generated in simulating subtask i

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for operator j, then in the original scheme t_{ij} is given by:

$$t_{ij} = \begin{cases} \dfrac{V_{ij} F_j}{S_{ij}} & \text{if } S_{ij} < M_j \\[2ex] [(2S_{ij} + 1 - 2M_j) V_{ij} - (S_{ij} - M)\overline{t}_{ij}] F_j & \text{if } M_j \leq S_{ij} \leq M_j + 1 \\[2ex] [3V_{ij} - \overline{t}_{ij}] F_j & \text{if } S_{ij} > M_j + 1 \end{cases}$$

where $V_{ij} = \overline{t}_{ij} + K_{ij} \overline{\sigma}_{ij}$

and K is defined as before.

Alternate Execution Time Calculation

A revised function for t_{ij} has been derived and is effective only in the region in which the augmented stress of the operator is below his threshold. This revised function therefore replaces only the first of the three formulae above. It was determined as a result of data collected during laboratory investigations in connection with a prior man-machine simulation (Siegel, Wolf, and Sorenson, 1962). A discussion of the derivation of the function is given in Appendix A. The revised execution time is:

$$t_{ij} = F_j V_{ij} Z_{ij} \qquad \text{if } S_{ij} < M_j$$

$$Z_{ij} = -1.8290 \left(\frac{S_{ij} - 1}{M_j - 1}\right)^3 + 3.4722 \left(\frac{S_{ij} - 1}{M_j - 1}\right)^2$$
$$-2.35075 \left(\frac{S_{ij} - 1}{M_j - 1}\right) + 1.0$$

The effect of the above is to provide a t_{ij} value selected from a normal distribution in which the values of $\bar{t}_{ij}$ and $\bar{\sigma}_{ij}$ are:

1. used unchanged when stress equals unity

2. decreased linearly (alternate: cubic function) with increasing stress until stress assumes the threshold value

3. used unchanged when stress equals the threshold value

4. increased linearly with increasing stress beyond the threshold until, when stress equals M_j+1, the contributions of $\bar{t}_{ij}$ and $\bar{\sigma}_{ij}$ remain constant at $2\bar{t}_{ij}$ and $3\bar{\sigma}_{ij}$ respectively.

The comparison of these functions is shown graphically in Figure 2.

Subtask Success and Failure

The model assumes that the actual probability of successful performance of a given subtask, p_{ij} is a function of $\bar{p}_{ij}$, s_{ij}, and M_j, as follows:

$$
p_{ij} = \begin{cases}
\bar{p}_{ij} + \dfrac{(1 + \bar{p}_{ij})(s_{ij} - 1)}{M_j - 1} & \text{if } s_{ij} < M_j \\[2ex]
\bar{p}_{ij}(s_{ij} + 1 - M_j) + (M_j - s_{ij}) & \text{if } M_j \leq s_{ij} \leq M_j + 1 \\[2ex]
2\bar{p}_{ij} - 1 & \text{if } s_{ij} > M_j + 1
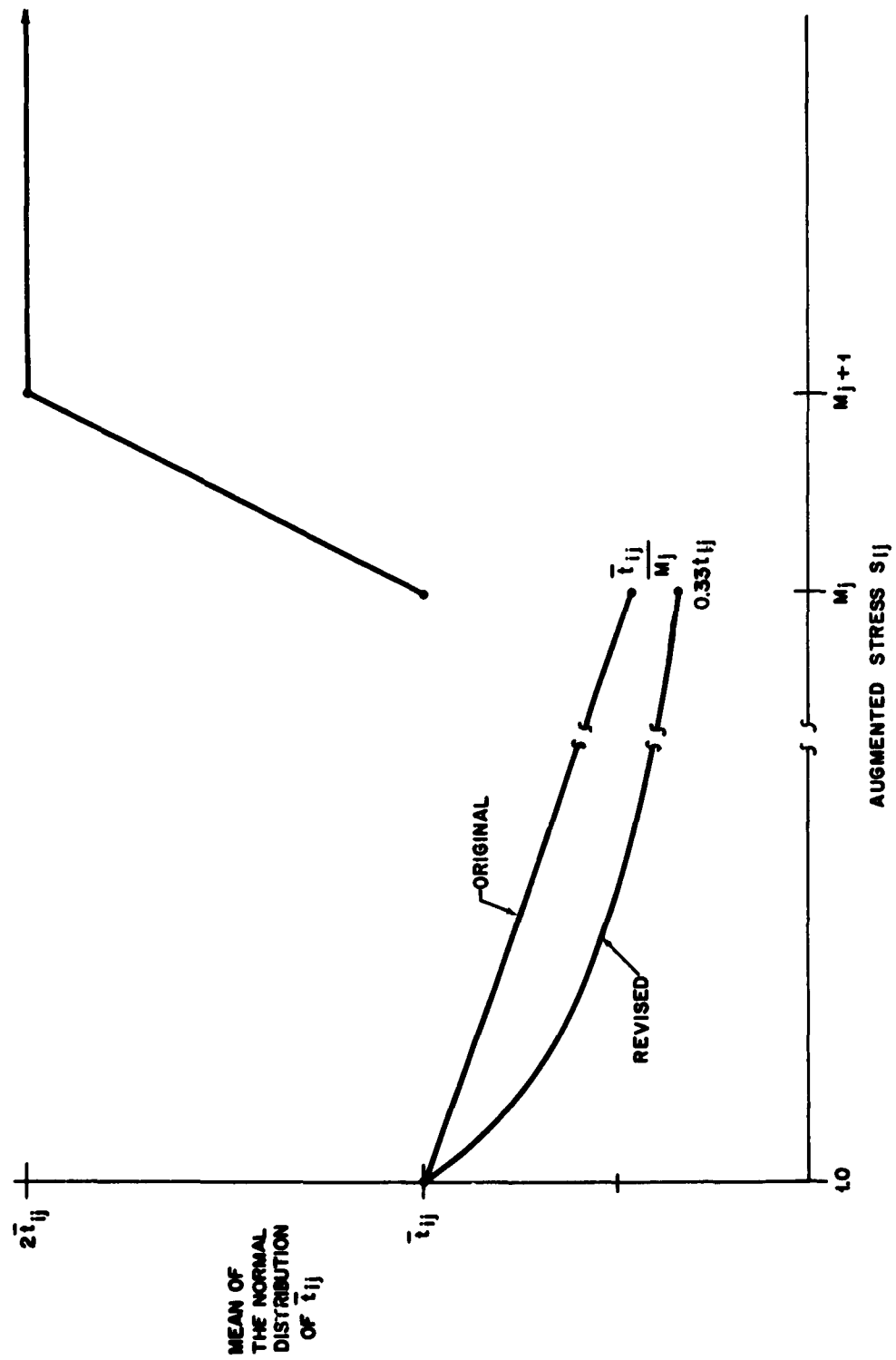\end{cases}
$$

Figure 2. Average execution time as a function of stress.

Thus, the probability of success increases linearly with stress from a value of $\bar{p}_{ij}$ until it assumes a value of unity at the stress threshold. Following this point, the probability assumes the average value, $\bar{p}_{ij}$ after which it decreases linearly until, when stress has a value equal to $M_j + 1$, it levels off at a value which is decreased from $\bar{p}_{ij}$ by an amount equal to $1 - \bar{p}_{ij}$. In order to determine actual success or failure for any subtask, the computer generates a pseudo-random number, R_3, uniformly distributed over the unit interval from R_2. The operator is considered to have performed the subtask successfully if R_3 is less than p_{ij}; otherwise he is assumed to have failed. This implies that there will be a failure with probability, $\bar{p}_{ij}$, in the long run.

To facilitate the calculation, these expressions were rearranged to indicate success if:

$$\frac{(M_j - 1)R_3 - s_{ij} + 1}{M_j - s_{ij}} < \bar{p}_{ij} \qquad \text{when } s_{ij} < M_j$$

$$\frac{s_{ij} - M_j + R_3}{s_{ij} - M_j + 1} < \bar{p}_{ij} \qquad \text{when } M \le s_{ij} \le M + 1$$

$$\frac{R_3 + 1}{2} < \bar{p}_{ij} \qquad \text{when } s_{ij} > M + 1$$

The computed left hand member of these inequalities is called the probability term and is made available as a printed result. In event of either success or failure, input information indicates the subtask which is performed next.

Multiple Action Subtasks

In certain subtasks, such as joystick and trim settings, several trials of the same action are usually required although a single action may occasionally be successful. These subtasks are organized for the computer as requiring a single control action with a relatively low probability of success. The probability of success on any single trial is determined, using the formula that if p is the probability of success on a single trial and p* is the probability of at least one success after n trials, then

$$p = 1 - \sqrt[n]{(1 - p^*)}$$

Team Decision and Special Subtasks

The remainder of computer operations (starting with the circled i of Figure 1) are concerned with bookkeeping, updating memory values, and special subtasks prior to recording of results. Special subtask type 1 provides the facility for one operator to make a decision for both himself and his partner. In this case, $\bar{p}_{ij}$ is the probability associated with this two-way decision. If R_3 is less than $\bar{p}_{ij}$ (normally called "success") then operator j takes his next subtask as indicated in $(i, j)_s$ and j' takes his from the special $(i, j)_s$. Similarly, if R_3 exceeds p_{ij}, then j goes to the subtask indicated by $(i, j)_f$ and his partner, to the subtask indicated by the special $(i, j)_f$.

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Special subtask type 1 can also be used to cause a sequence of subtasks performed by one of the operators to be dependent on whether or not his partner has skipped a given subtask. In this case (when I_{ij} is not negative, indicating the subtask is not a decision subtask), the sequence is as follows:

(a) j goes to $(i,j)_f$ if he performs and fails
(b) j goes to $(i,j)_s$ if he performs and succeeds
(c) j goes to special $(i,j)_s$ if he ignores the subtask
(d) j' goes to special $(i,j)_f$ if j ignores the subtask

Special subtask type 2 enables a single operator to skip one or a block of subtasks depending on whether or not he ignores a designated subtask. For example, if operator j ignores a type 2 subtask, then his next subtask will be the one indicated by the special $(i,j)_s$; if he does not skip, he will take $(i,j)_s$ next, and upon failure, he will continue with subtask $(i,j)_f$.

Recording of Results

The model is organized so that at the completion of calculations for one run, any combination of the following four sets of recorded results may be produced:

(1) Detailed results   - pertaining to individual subtasks

(2) Pseudo-random numbers   - pertaining to individual subtasks

(3) Intermediate results   - summary for each simulation or iteration

(4) Final results   - summary for all N iterations of a run

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An example of the results pertaining to each subtask (see circled q, Figure 1) is given in Table 2. Table 2 is a direct reproduction of data prepared by the high speed printing device from a magnetic tape record of a two-operator task. The table shows detailed results from one iteration followed by the corresponding intermediate results (circled u, Figure 1). All time and stress values have two decimal places.

Table 3 shows a sample from tabulations of the pseudo-random numbers, together with K and V_{ij} values. Here, leading blanks in the pseudo-random numbers are zeros; V_{ij} and K have two decimal places.

Table 4 shows an example of the results printed at the completion of each run.

Table 2

Sample of Detailed and Intermediate Results

Table 3

Sample of Pseudo-Random Number Results

Run	Trial	j	i		R_0		R_1		R_2		R_3		K		V_{ij}	Interrupt
008	C01	1	C1	R0	506033543	R1	375823727	R2	364741101	R3	506033543	K1	59-	V	145	INT
				R0	506033543	R1	853530629	R2	866881087	R3	419515661	K1	59-	V	145	INT
				R0	455392847	R1	294648541	R2	369355623	R3	664296869	K1	31-	V	180	
		2		R0	664296869	R1	961580607	R2	690811821	R3	190645463	K1	83	V	180	
			02	R0	190645463	R1	76566389	R2	743589167	R3	122437501	K1	64	V	150	
		1		R0	122437501	R1	742322503	R2	451997509	R3	331082527	K1	130-	V	109	
		2	03	R0	331082527	R1	818517581	R2	631362743	R3	521518229	K1	169	V	207	
		1		R0	521518229	R1	746844687	R2	687404061	R3	102822183	K1	87	V	139	
			04	R0	102822183	R1	530296549	R2	556379647	R3	465608941	K1	60-	V	154	
		2		R0	465608941	R1	486236823	R2	826940469	R3	885511407	K1	7-	V	199	
		1	C5	R0	885511407	R1	770604221	R2	354022663	R3	288697589	K1	21-	V	167	
			06	R0	288697589	R1	845583967	R2	377621901	R3	351875703	K1	20	V	167	
			07	R0	351875703	R1	812657109	R2	9061327	R3	640453581	K1	110	V	125	
		2	05	R0	640453581	R1	441171943	R2	102945829	R3	767127487	K1	97	V	557	
		1	C8	R0	767127487	R1	576252441	R2	253367383	R3	433932149	K1	15-	V	74	
			C9	R0	433932149	R1	623286447	R2	734329341	R3	496398C23	K1	94-	V	122	
		2	06	R0	496358023	R1	469424C69	R2	648962207	R3	568956621	K1	6	V	120	
			07	R0	568956621	R1	273079863	R2	617869589	R3	549498767	K1	34	V	145	
		1	10	R0	549498767	R1	636166301	R2	571508903	R3	803556709	K1	139-	V	80	
		2	C8	R0	803556709	R1	977760127	R2	534550381	R3	107461143	K1	40-	V	144	
		1	11	R0	107461143	R1	933813429	R2	535730287	R3	110060861	K1	115	V	148	
		2	C9	R0	110060861	R1	938792583	R2	742207749	R3	304113247	K1	121-	V	471	
		1	12	R0	304113247	R1	44809741	R2	231839223	R3	87747669	K1	115	V	142	
			13	R0	87747669	R1	739933007	R2	549869021	R3	339817C63	K1	135-	V	56	
			14	R0	339817063	R1	19CC81109	R2	302133567	R3	482070701	K1	41-	V	316	
		2	10	R0	482070701	R1	153222103	R2	680696309	R3	5178927	K1	39	V	146	
			11	R0	5178927	R1	804806781	R2	48223C343	R3	750121029	K1	221-	V	115	
		1	15	R0	750121029	R1	460653087	R2	912829261	R3	31097783	K1	69	V	141	
		2	12	R0	31C97783	R1	71123349	R2	446860047	R3	941050141	K1	16	V	293	
		1	16	R0	941050141	R1	324560429	R2	577911269	R3	846423807	K1	30	V	135	
			17	R0	846423807	R1	777341421	R2	746234263	R3	581332789	K1	17	V	152	
			18	R0	581332789	R1	71888367	R2	99335101	R3	649015303	K1	81	V	198	
		2	13	R0	649015303	R1	190075909	R2	59317727	R3	355223181	K1	209-	V	107	
				R0	355223181	R1	257479543	R2	687060629	R3	749895887	K1	16	V	143	
		1	19	R0	749895887	R1	208557661	R2	202282983	R3	436678949	K1	32	V	135	
			20	R0	436678949	R1	99526847	R2	567050541	R3	206561623	K1	5-	V	129	
		2	14	R0	206561623	R1	235914869	R2	856434607	R3	915373821	K1	56-	V	71	
		1	21	R0	915373821	R1	484331463	R2	767624389	R3	546763167	K1	26-	V	67	
		2	15	R0	546763167	R1	271959501	R2	410888503	R3	117695509	K1	51	V	148	
		1	22	R0	117695509	R1	3C8176527	R2	689799581	R3	65208743	K1	179	V	159	
		2	16	R0	65208743	R1	283056229	R2	411458687	R3	821246061	K1	40	V	86	
			17	R0	821246061	R1	924348183	R2	254874549	R3	510113647	K1	160-	V	114	
			18	R0	510113647	R1	666810941	R2	109842823	R3	757758469	K1	52	V	298	

Table 4

Sample of Summary (Run) Results

Run	Trial	N	Initial R_0	Note	Number of Successes	Failures	Number of Interrupts	Successes with Interrupts	Average Waiting Time	Average Terminal Stress	Average Terminal Cohesiveness	Average Peak Stress	Average Time Remaining
008	01	010	506033543	00118	009	001	005	004					
		j 1		F 1000 M		0200 Aver 000000			000454	0112	0035	0167	000144
		2		j 1000 j		0200 Idle 000000			000481	0140	0030	0181	0001'7
						Time							

i	Last Subtask Completed j = 1	j = 2	Number of Subtasks Failed j = 1	j = 2	Number of Subtasks Ignored j = 1	j = 2
01	00000	00000	00000	00000	00000	00000
02	00000	00000	00000	00000	00000	00000
03	00000	00000	00001	00001	10000	00000
04	00000	00000	00000	00000	00000	00000
05	00000	00000	00000	00001	00000	00000
06	00000	00000	00001	00000	00000	00000
07	00000	00000	00000	00000	00000	00000
08	00000	00000	00000	00000	00000	00000
09	00000	00000	00000	00001	00000	00000
10	00000	00000	00000	00000	00000	00000
11	00000	00000	00000	00000	00000	00000
12	00000	00000	00001	00000	00000	00000
13	00000	00000	00000	00001	00000	00000
14	00000	00000	00000	00000	00000	00000
15	00000	00000	00000	00000	00000	00000
16	00000	00000	00000	00000	00000	00000
17	00000	00000	00000	00001	00000	00000
18	00000	00000	00000	00001	00000	00000
19	00000	00000	00000	00001	00000	00000
20	00000	00000	00000	00000	00000	00000
21	00000	00000	00000	00000	00000	00000
22	00000	00000	00000	00000	00000	00000
23	00000	00000	00000	00000	00000	00000
24	00000	00000	00000	00000	00000	00000
25	00000	00000	00000	00000	00000	00000
26	00000	00000	00000	00000	00000	00000
27	00000	00000	00001	00000	00000	00000
28	00000	00000	00000	00001	00000	00000
29	00000	00000	00000	00000	00000	00000
30	00000	00000	00000	00000	00000	00000
31	00000	00000	00001	00000	00000	00000
32	00000	00000	00000	00000	00000	00000
33	00000	00000	00000	00000	00000	00000
34	00000	00000	00000	00000	00000	00000
35	00000	00000	00000	00000	00000	00000
36	00000	00000	00000	00000	00000	00000
37	00000	00000	00000	00000	00000	00000
38	00000	00000	00000	00000	00000	00000
39	00000	00000	00000	00001	00000	00000
40	00000	00000	00000	00000	00000	00000
41	00000	00000	00000	00000	00000	00000
42	00000	00000	00000	00007	00000	00000
43	00000	00000	00000	00001	00000	00000
44	00000	00001	00001	00000	00000	00000
45	00000	00000	00000	00000	00000	00000
46	00000	00000	00000	00000	00000	00000
47	00001	00000	00000	00001	00000	00000
48	00000	00000	00000	00000	00000	00000
49	00000	00000	00000	00000	00000	00000
50	00000	00009	00000	00000	00000	00000
51	00000	00000	00000	00000	00000	00000
52	00000	00000	00000	00000	00000	00000
53	00000	00000	00000	00000	00000	00000
54	00009	00000	00001	00000	00000	00000

CHAPTER III

COMPUTER UTILIZATION

This chapter contains information on the operation of the IBM 705 III computer for the man-machine digital simulation. These instructions for the operator of the equipment, dealing primarily with card and magnetic tape formats, are presented for those who may be interested in applying the digital simulation technique described.

Card Formats

Figure 3 shows the composition of the computer input data card deck. Figure 3 displays six card types whose contents and format are shown in Figure 4. Note that the three data cards for the first desired run are placed in front of the card deck of operator data sets; the triplets of cards for as many additional runs as are desired are placed after the operator data. In Figure 4 a + sign indicates the card column in which the sign of the data field is given. In accordance with standard card codes Table 5 shows the proper card punch for these columns which combines the sign and digit.

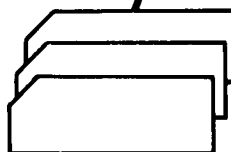CARD NUMBER FORMAT   CARD TYPE
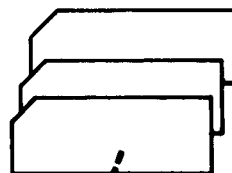
3
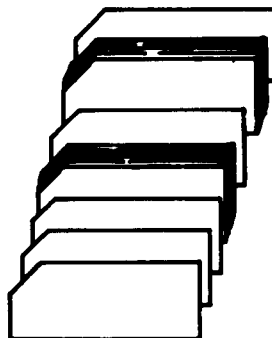2   INITIAL CONDITIONS
1   AND PARAMETERS,
                               LAST RUN.

                        ETC.

3
2   INITIAL CONDITIONS
1   AND PARAMETERS,
                               SECOND RUN.

6
4   SUBTASK DATA, END CARD

5   SUBTASK DATA, SECOND OPERATOR

4   OPERATOR'S SUBTASK SEPARATOR CARD

3   SUBTASK DATA, FIRST OPERATOR
2   PARAMETERS, SECOND OPERATOR
1   PARAMETERS, FIRST OPERATOR
                               INITIAL CONDITIONS

Figure 3. Input card composition.

MULTIPLE LAYOUT FORM
FOR ELECTRIC ACCOUNTING MACHINE CARDS

Figure 4. Input card formats.

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Table 5

Proper Card Punch for Signed Columns

| | Proper Card Punch | |
Digit	+ Sign	- Sign
	+	
0	0	
1	A	J
2	B	K
3	C	L
4	D	M
5	E	N
6	F	O
7	G	P
8	H	Q
9	I	R

Options of the Model

The six Alteration Switches on the computer operator's console have been utilized in the man-machine model to provide options to the analyst-programmer, as shown in Table 6. In addition, if it is desired to employ the revised method of determining the urgency condition, an F is prestored at location 39000 prior to computation. Otherwise, the original method is utilized (see Chapter II - Urgency and Stress section).

Table 6

Alteration Switch Functions

Alteration Switch Numbers	ON Condition	OFF Condition	Notes
911	Record only subtask failures, intermediate and summary results	Other switches apply	If ON, 912 and 913 must be OFF
912	Record detail for first iteration only, all intermediate and summary results	Other switches apply	If ON, 911 and 913 must be OFF
913	Record all subtask detail, and all summary results	Other switches apply	If ON, 911 and 912 must be OFF
914	Utilize revised (cubic) function for t_{ij}	Utilize original (linear) function for t_{ij}	See Chapter II and Figure 2
915	Read inputs from tape	Read inputs from cards	
916	Record pseudo-random number data	Do not record pseudo-random number data	See Table 3

Operator Instructions

Prior to starting the one or more runs, tne instruction tape is loaded on drive 0600, and two blank, or scratch magnetic tapes, are loaded on drive 0601 and 0605. Punched card inputs in the form shown in Figure 4 are loaded into the card reader, station 0100. To begin, load the program from tape using the following instructions: 20600 (select 600), 30018 (cpntrol 18), Y000 (read 0), reset, and start. The program will be read in, followed by card data, and there will be a HALT to allow the operator to set the Alteration Switches and to load an F in 39000, if desired. The calculation may then be initiated. Experience has suggested the computer takes about 0. 25 seconds to simulate each operator subtask. Detail, intermediate, and summary results are recorded on tape drive 0601 in the format of Tables 2 and 4. The pseudo-random number data of Table 3 are recorded on tape drive 0605, if selected. The tapes may be printed via the standard IBM 1401 print programs. After each run, the computer halts to allow changes in Alteration Switches and the F at 39000.

A detailed listing of the assembled man-machine simulation program is obtainable on a loan basis from Applied Psychological Services and will be loaned to responsible agencies and organizations on an inter-library loan basis.

CHAPTER IV

THE ONE-OPERATOR TASK

Task Description and Analysis

The present study involved the simulation of a pilot's task when firing an air-to-air missile in a lead collision attack, as reported by Siegel and Wolf (1959b). In the missile firing, proceeding at a speed of about 800 feet per second, the attack begins when the target is approximately 30 miles distant; the attack is concluded when at least two miles separate the target from the interceptor. It was assumed that the pilot would take advantage of every available moment until he was two miles distance (breakaway point) to execute the sequence of subtasks. The value of T was determined from the best estimate of the distance traveled by the intercept aircraft (28 miles including maneuvers) and his speed of about 800 feet per second. Thus, the value of T selected was 184.8 seconds. A general diagram of the missile launching operation is presented as Figure 5. A simulation run was considered successful only if all subtasks, including breakaway, were completed prior to T elapsed seconds. In practice, if insufficient time remained to complete the required operations action prior to missile launch, the pilot would, of course, give up the launching sequence and breakaway. The task analysis data, previously derived, were put into the two-man model format and are shown in Table 7. These data are given in the format of card type 4 of Figure 4.
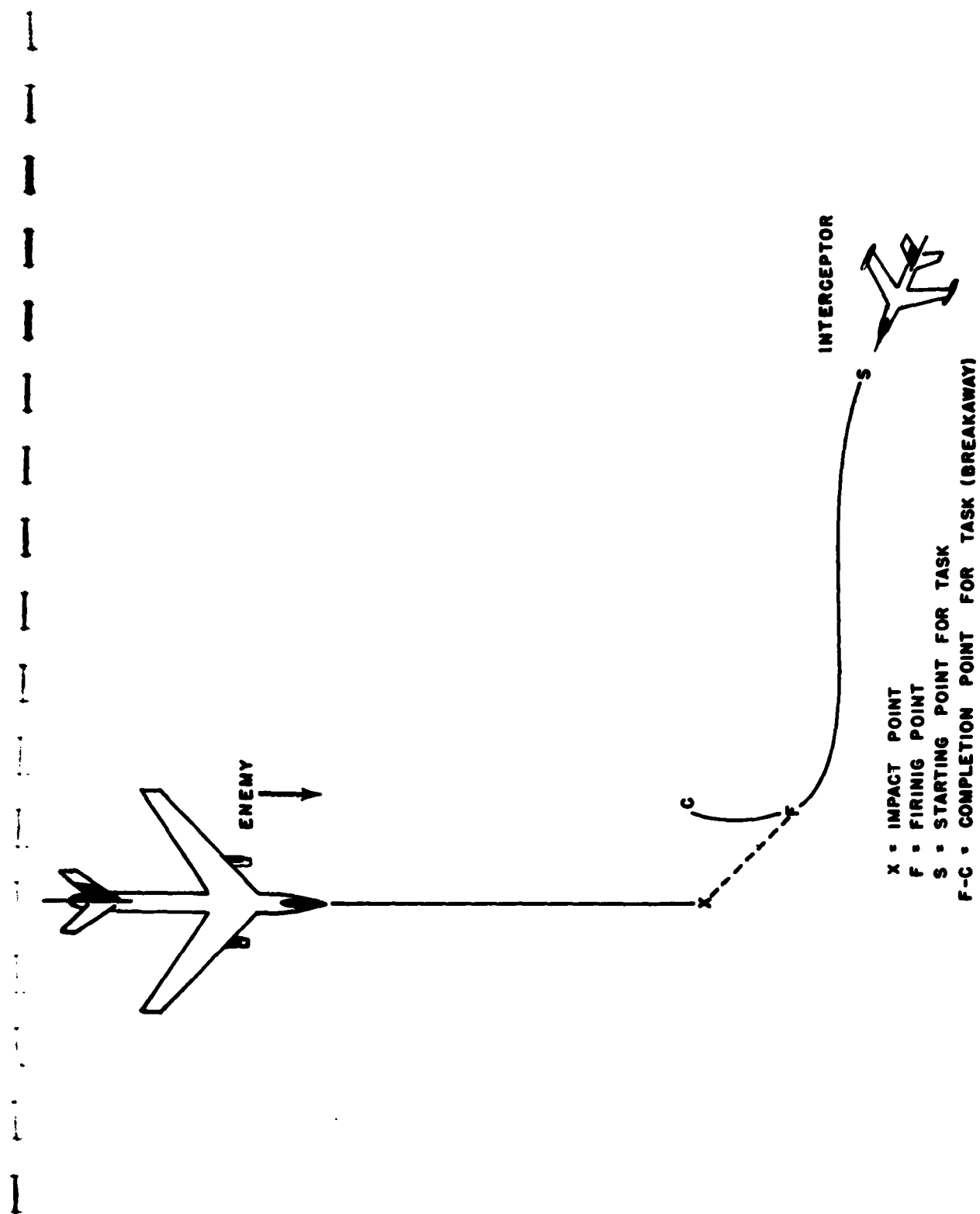
X = IMPACT POINT
F = FIRINIG POINT
S = STARTING POINT FOR TASK
F-C = COMPLETION POINT FOR TASK (BREAKAWAY)

Figure 5 Diagram of the launching operation (not drawn to scale)

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Table 7

Task Analysis Data for One Man Air-to-Air Missile Firing Task

i	$\bar{t}_{ij}$	$\bar{\sigma}_{ij}$	$\bar{\rho}_{ij}$	E_{ij}	$(i,j)_f$	$(i,j)_s$	d_{ij}	Comm	T^E_{ij}	T^N_{ij}	L_{ij}
						OPERATOR 2					
1	3.8	0.48	0.537	1	1	2	0	0	151.7	12.0	0
2	20.0	5.00	0.900	1	2	3	0	0	147.9	12.0	0
3	3.8	1.40	0.900	0	3	4	0	0	127.9	12.0	0
4	11.4	1.44	0.960	1	4	5	0	0	118.5	8.4	0
5	16.8	4.08	0.990	1	5	6	0	0	99.7	8.4	0
6	8.4	2.04	0.990	1	6	7	0	0	91.3	8.4	0
7	20.0	5.00	0.990	0	7	8	0	0	71.3	8.4	0
8	2.4	1.00	0.990	1	8	9	0	0	71.3	6.0	0
9	3.8	0.48	0.250	1	10	10	0	0	67.5	6.0	0
10	2.2	1.52	0.990	1	11	11	0	0	63.7	6.0	0
11	6.0	3.00	0.190	1	12	12	0	0	61.5	6.0	0
12	0.0	0.00	0.750	0	14	13	0	0	55.5	6.0	0
13	10.0	3.00	0.900	1	14	15	0	0	55.5	6.0	0
14	6.0	0.48	0.280	1	15	15	0	0	45.5	0.0	0
15	3.8	1.02	0.970	0	16	16	0	0	45.5	0.0	0
16	4.2	1.20	0.970	1	17	17	0	0	41.7	0.0	0
17	3.0	0.48	0.850	1	18	18	0	0	37.5	0.0	79.2
18	3.8	0.00	0.970	0	19	20	0	0	34.5	0.0	0
19	0.0	0.48	0.140	1	21	25	0	0	00.0	0.0	0
20	3.8	0.48	0.540	1	21	22	0	0	23.2	0.0	0
21	3.8	1.02	0.990	1	22	23	0	0	19.4	0.0	0
22	4.2	1.44	0.990	0	23	24	0	0	15.6	0.0	0
23	11.4	1.44	0.990	1	24	END	0	0	11.4	0.0	0
24	0.0	0.48	0.500	1	31	26	0	0	00.0	0.0	0
25	3.8	0.48	0.100	1	26	27	0	0	34.8	0.0	0
26	3.8	1.44	0.540	1	27	28	0	0	30.8	0.0	0
27	11.4	1.02	0.990	1	28	29	0	0	27.0	0.0	0
28	4.2	0.48	0.990	1	29	30	0	0	15.6	0.0	0
29	11.4	0.48	0.990	1	30	END	0	0	11.4	0.0	0
30	3.8	0.90	0.080	1	31	32	0	0	34.3	0.0	0
31	1.8	1.97	0.970	1	32	33	0	0	30.5	0.0	0
32	12.0	0.76	0.990	1	33	34	0	0	28.7	0.0	0
33	1.1	1.02	0.990	1	34	35	0	0	16.7	0.0	0
34	4.2	1.44	0.990	1	35	36	0	0	15.6	0.0	0
35	11.4			1	36	END	0	0	11.4	0.0	0
						OPERATOR 1					
1	0.0	0.00	0.999	0	2	3	0	0	1.0	1.0	0

The launching task is divided into 22, 23, or 24 basic subtasks from the start of the maneuver to the final breakaway.

Following subtask 19, a decision is possible (subtasks 20 and 25) in accordance with the following (at least) three equally probable alternatives:

(1) the target is properly centered on the radar scope; therefore subtasks 21 through 24 are to be performed

(2) the target is too high on the radar scope; therefore subtasks 26 through 30 must be performed

(3) the target is too low on the radar scope; therefore subtasks 31 through 36 must be performed

Because of the nature of the launching task, subtask number 18 could not be initiated until "lock-on" had occurred. This was allowed after a minimum of 79.2 seconds following the start of the maneuver.

The interrupt feature was not used in this particular task sequence.

Outside Criterion

In order to obtain some measure of the agreement between the results obtained from the model and the actual performance of pilots, data has been obtained previously (Siegel and Wolf, 1959b) which indicate actual pilot launch results. These data, called the outside criterion, were compiled from the launching data of 11 pilots. The data indicated that 713 missile launching attempts out of 876 were successful, an overall probability of task success of 81.4%. Here, success indicates completion of all subtasks involved in missile launching and does not necessarily imply a "kill. "

Verification Data Runs

A total of 18 computer runs were performed initially to verify that the two-man model (prior to any modifications) gave reasonable data, as well as results consistent with the data obtained previously using the one-man simulation model. Each run consisted of 88 simulations with a time limit of 184. 8 seconds, as before. Each required about nine minutes of computation (as compared to one hour of computing on the IBM 650 Data Processing Machine using a simpler model). The principle result of this effort--that with respect to failure probability--is shown in Figure 6. Close agreement was achieved in the frequency of failure for each of the five values of the individuality factor (F_j) tested. The agreement displayed is considered well within the accuracy limits of the model as described for this type of distribution with $N = 88$ (Siegel and Wolf, 1959b, p. 16). The outside criterion data for failures (18. 6%) is equivalent to 16. 3 failures in 88 trials, and is shown on Figure 6 as an arrow at the ordinate. As reported for the one-man model, the model's predictions were in agreement with the outside criterion data only for fast operators (faster than about 0. 91).
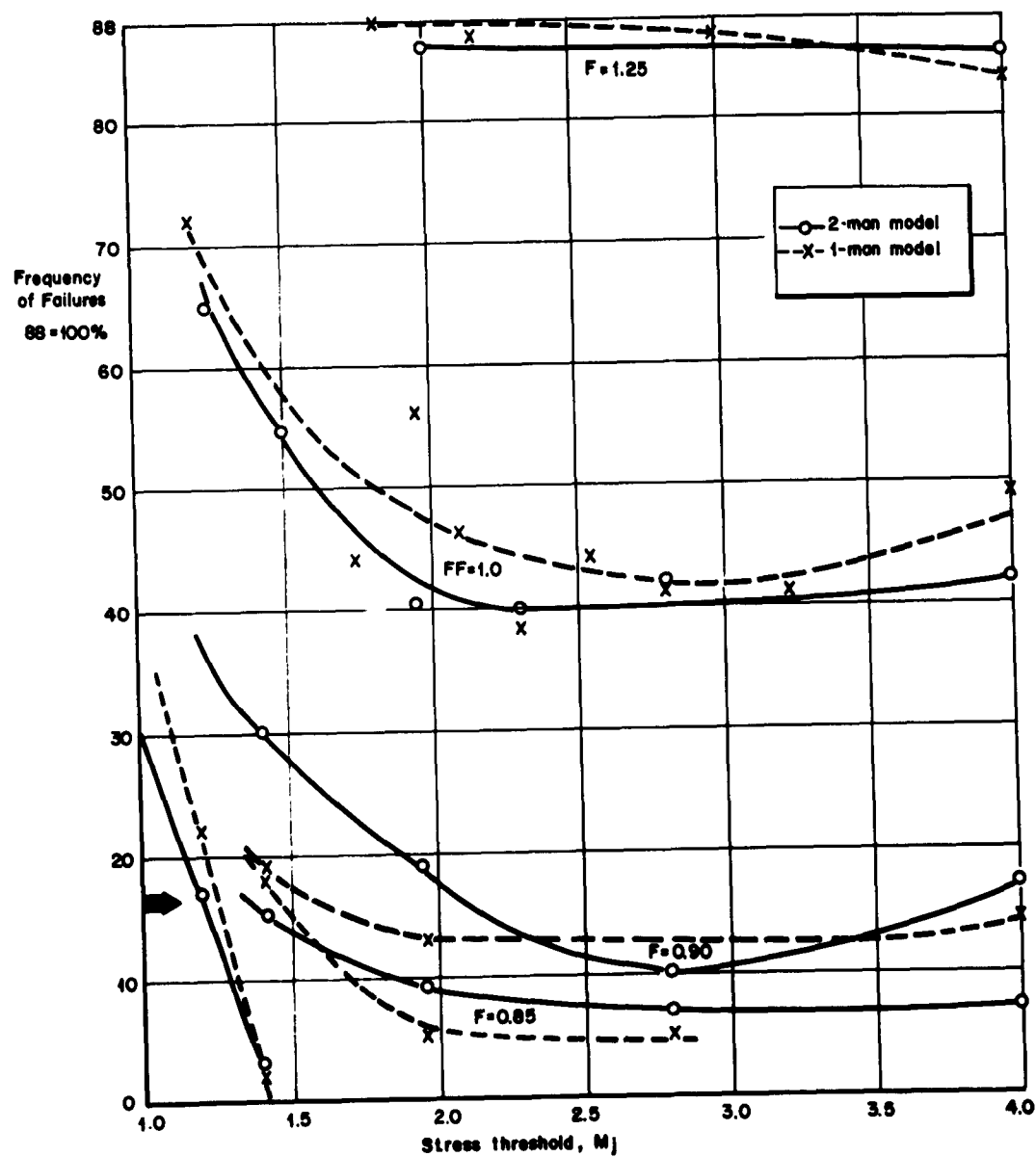
Figure 6. Results of Verification Data Runs.

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Task Success--Modified Model

Following these computations, 15 additional runs were made on the computer to determine effects of the changes to the model on its performance. Table 8 shows the principal summarized results. Two runs of 88 iterations were made for each of the F_j = 1.0 entries and the results averaged; one run was made for the other F_j values. A failure here indicates a simulation in which the task was not completed by the simulated operator within the time limit--completion is achieved by accomplishment of subtask 24, 30, or 36. A graphic display of the frequency of failure is given in Figure 7. Again the outside criterion value, 18.6% or 16.3 out of 88 failures is indicated by an arrow at the abscissa. The major result is that for the average operator (F_j = 1.0), the revised model now predicts a failure frequency which corresponds to the outside criterion value. This occurs at a stress threshold (M_j) range value of 1.41 and 2.70. This range of M_j values is reasonable in that it is in reasonable agreement with the range of M_j values (1.9 to 2.8) for which agreement between the model and reality has been previously predicted (Siegel and Wolf, 1961b).

For comparison, the predicted failure frequency curve of the unmodified model (for F_j = 1) is shown as a line of Xs in Figure 7.

Table 8

Simulation Results Using the Modified Model

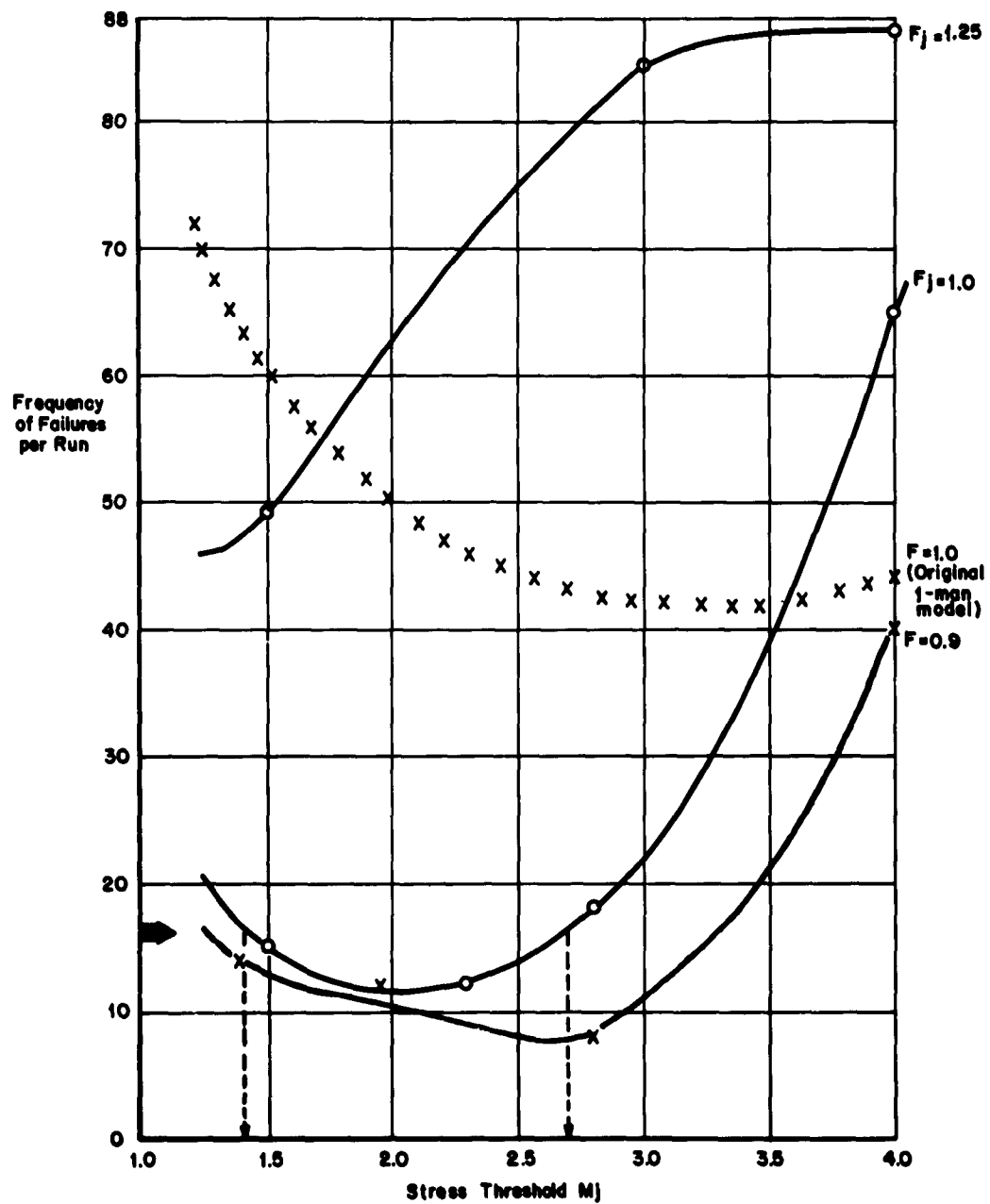| *Previous Run No.	F_j	M_j	Number of Failures out of 88	Time Remaining (secs.)	Average Terminal Stress	Average Peak Stress
7	0.9	1.40	14	4.0	1.1	1.3
8		1.95	12	3.5	1.1	1.4
9		2.80	8	2.9	1.4	1.6
10		4.00	40	2.2	1.9	2.1
12	1.0	1.50	15	2.7	1.1	1.4
16		2.30	12	1.8	1.3	1.7
18		2.80	18	1.3	1.6	1.9
20		4.00	65	1.9	2.4	2.5
22	1.25	1.50	49	1.9	1.5	1.7
24		3.00	84	0.2	2.8	2.9
25		4.00	87	13.2	4.3	4.3

* Siegel and Wolf, 1959b

Figure 7. Frequency of Task Failure, Revised Model.

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Time Remaining--Modified Model

An important use of the model could be to provide quantitative predictions on how much time remains to the operator after his task is completed. No field data were available for the launching task against which to check these computed results for reasonable correspondence with reality. Although these data may have limited value in the validation of the model, they would be important when investigating or comparing proposed man-machine systems.

The average time remaining (in seconds) after task completion for each simulated run is given in Table 8 and displayed in graphic form in Figure 8. The data are based only on those simulations which were successful (i.e., subtask 24, 30, or 36 completed). Although the data are based on a very small sample of successful simulations for some runs, they are sufficient to indicate, as would be expected, the average time remaining decreases with increasing M, and with decreasing F values.

This is in confirmation of the trend of results achieved on the one-man model. For comparison purposes, the time remaining for the average operator using the one-man model is shown in Figure 8 as a line of Xs. For the stress threshold values which give a correspondence of the model with outside criterion data in failure frequency (M = 1.4 - 2.7), the revised model indicates an average of only 1.3 to 2.8 seconds to remain after successful subtask completion.

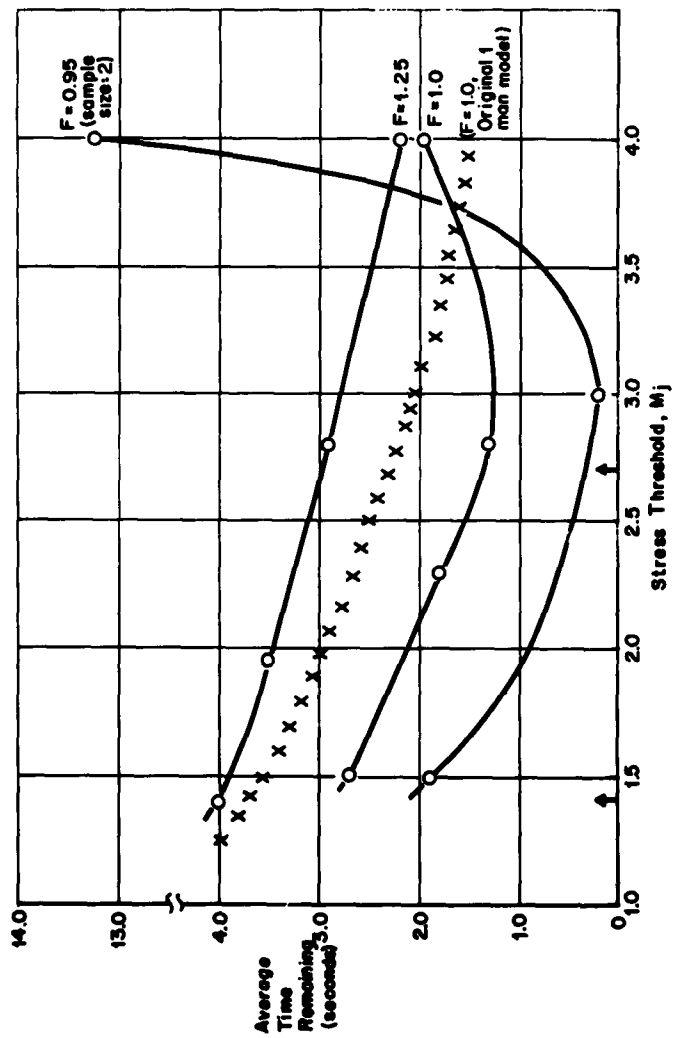- 44 -

Figure 8. Average Time Remaining

Peak and Terminal Stress

Figure 9 presents the average peak stress conditions and the stress conditions at the end of the computer runs. As expected, and as experienced in previous tests of the model, both the peak and the terminal stress values increased with increasing F_j values; this indicates that slower operators may be expected to build up greater stress than faster ones. This finding also reflects the fact that slower operators complete less work in a given time and consequently their $T_j - T_{ij}^U$ values (on which stress depends) are lower.

Discussion

The quantitative outside criterion datum available on the selected task was success probability. The results presented above suggest that the present model, as modified, generated predictions for the task considered which are in good agreement with the criterion data. Qualitatively, the model also yielded results for other variables whose trends were reasonable and consistent. These variables include:

1. time remaining after task completion
2. average stress after task completion
3. average peak stress

These are the primary summary data of interest produced by the computer model for this task. Other information, including idle times, second operator data, nonessential subtasks ignored, and interrupt results do not apply to the particular one-man task selected due to the inherent nature of the task.
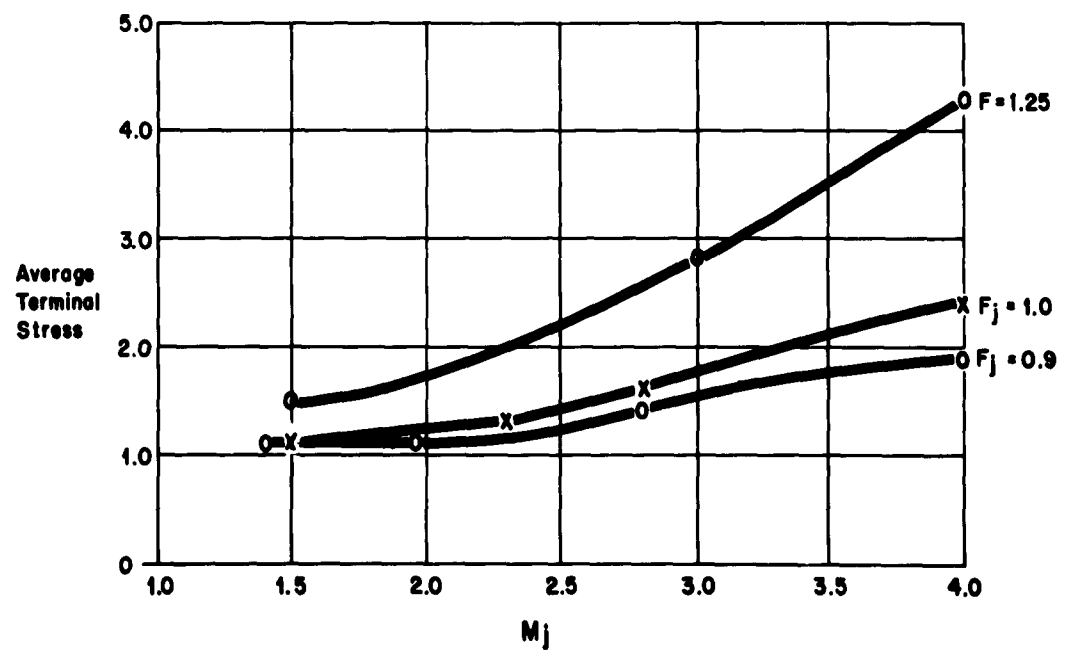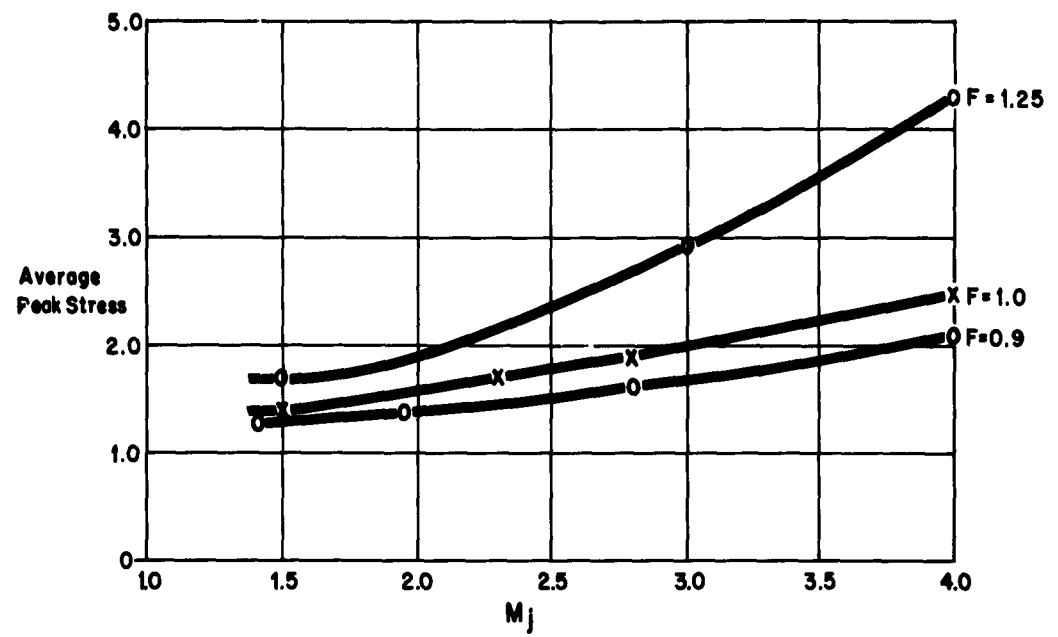
Figure 9. Peak and terminal stress.

Thus, two conclusions may be inferred from the results presented. The first is that the present model has been shown to possess qualities and to generate results which represent and show a state of development for the model for the task simulated and by implication for a task of the complexity of 20-30 subtasks and with gross accuracy estimated to be about 5% to 10%. Thus, this application has shown another in a series of encouraging results and represents another small step toward the larger goal of generalized man-machine system simulation.

The second point is that, due to the nature of the criterion data, this work, although a valid and reasonable test, represents only a limited accomplishment in model verification from the quantitative aspects. The simulated dual operator experiment (Siegel, Wolf, and Sorenson, 1962) partially compensates, to some degree, for this lack by providing a controlled experiment with more extensive outside criteria data. However, to evaluate further the model and the recent modifications (random interrupt, special subtasks, etc.) another controlled experiment was planned and recently executed.

Corresponding computer runs have also been made. A report on this research from the Applied Psychological Services is scheduled for distribution in October, 1963, and is expected to represent still another step in the validation of this type of model.

One additional benefit of this model should be discussed. It is the availability of the extensive data from the detailed (i.e., individual) simulations. In this report, 88 trials or simulations were computed for each run.

Thus, if desired, the system designer or applications engineer could have obtained, in addition to the summerized data reported and displayed above, a detail printout of the timing, actions, stress (and for a two-man task interaction, delays, interrupts, etc.) for every subtask simulated. A substantial benefit could be derived from these data on a task which represents a new or untried system or equipment. The ranges of values for times of performance of specific subtasks, as well as the stress level at critical points would be particularly important. Comparative evaluation of these detail (subtask) data under various parameter value conditions could be exceptionally valuable. It is also believed that the "feel" for the task derived by a thorough study of selected detail data including the level of task complexity, operator timing, and stress would be even more important to man-machine design assistance than the summary data against which the model must be verified in its present state of development. Although much care must be exercised in the preparation of the task analytic data, it is now considered that for selected one or two-operator tasks the model would presently be utilized for general system characterization and comparative system evaluation both at the summary and detail results level.

CHAPTER V

SUMMARY AND CONCLUSIONS

The applicability of a digital computer model for simulating the actions of the operator of a two-operator man-machine system for uni-operator simulations was tested. Although logical expectancy suggested the applicability of the model to this purpose, no test of its usability in this regard had been previously performed.

Then, in order to increase the richness of the simulation, a number of modifications were introduced into the model. These modifications involved a number of logic changes to allow consideration of: (1) the individuality factor in the urgency and stress calculations, (2) random interrupts, and (3) equipment imposed delays. Additional changes involved a limitation on the maximum possible operator stress and a new stress function. The model in its present form was described in detail in the body of this report. To test the effects of these modifications, the results from the simulation were compared with criterion data using both the former and the revised model.

The data emerging from the first aspect of the work suggested that:

1. the multi-operator model is usable for uni-operator simulations

The comparison of the results of the revised and the previous model with criterion data suggested that:

2. the modifications increased the obtained agreement between the simulation technique and criterion data

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APPENDIX A

Derivation of Revised t_{ij} Function

DERIVATION OF REVISED t_{ij} FUNCTION

A byproduct of laboratory experiments conducted in support of verifi-
cation of the two man-model (Siegel, Wolf, and Sorenson, 1962) was a group of
data which has been used as a basis for determining a revised function for t_{ij}, the
execution time of subtask i by operator j. Data from three subjects was normal-
ized to determine execution time as a function of the stress level S_{ij}, and the
stress threshold, M_j. This function is valid only over the interval:

$$1.0 \leq S_{ij} \leq M_j$$

A simple detented rotary control activation situation, consisting of 31
switch settings, was employed in the test. Each subject was initially asked to
make 31 rotary control settings at a rapid, but comfortable, pace. These initial
settings were used to obtain his average time required to set the 31 controls. He
was then asked to try to make the same 31 settings when his time limit was 0.95
of his normal time; then 0.90 of his normal time; and so on until the time allowed
was 0.35 of his normal time.

The stress relationship described in Chapter II was assumed:

$$S_{ij} = \frac{\overline{T}_{ij}^{E}}{T_j - T_{ij}^{U}}$$

where $\overline{T}_{ij}^{E}$ = 31 (time per switch setting with no stress)

$\overline{T}_{ij}^{U}$ = 0 (assume the beginning of 31 operations)

T_j = average time for the 100% case (no stress)

It was also assumed as an approximation that the following relation-ship holds:

$$t_{ij} = \frac{\bar{t}_{ij} F_j}{s_{ij}}$$

Values for F_j and M_j for the operators were previously determined via laboratory experiment. For each of the fourteen 5% data trials (from 100% to 35%) the following data were computed for each of the three subjects:

(1) actual time observed, per switch

(2) nominal non-stressed time for 31 switches

(3) stress, S_{ij}

(4) adjusted execution time, t_{ij}

(5) $\frac{S_{ij} - 1}{M_j - 1}$, (normalizes stress from 1 to M_j into the common interval 0 to 1)

(6) $\frac{t_{ij}}{\bar{t}_{ij} F_j}$, (normalizes the execution time to the average, and adjusts for F_j)

A plot (Figure 10) was then made for the three operators showing $\frac{t_{ij}}{\bar{t}_{ij} F_j}$ as a function of $\frac{S_{ij} - 1}{M_j - 1}$. Several approaches were taken to fit an analytical expression to the data given in Figure 9.

The technique selected (Scarborough, 1950) enabled the determination of the three constants of the cubic, given that $\frac{t_{ij}}{\bar{t}_{ij} F_j} = 1.0$ when $S_{ij} = 1.0$. The resultant cubic was:
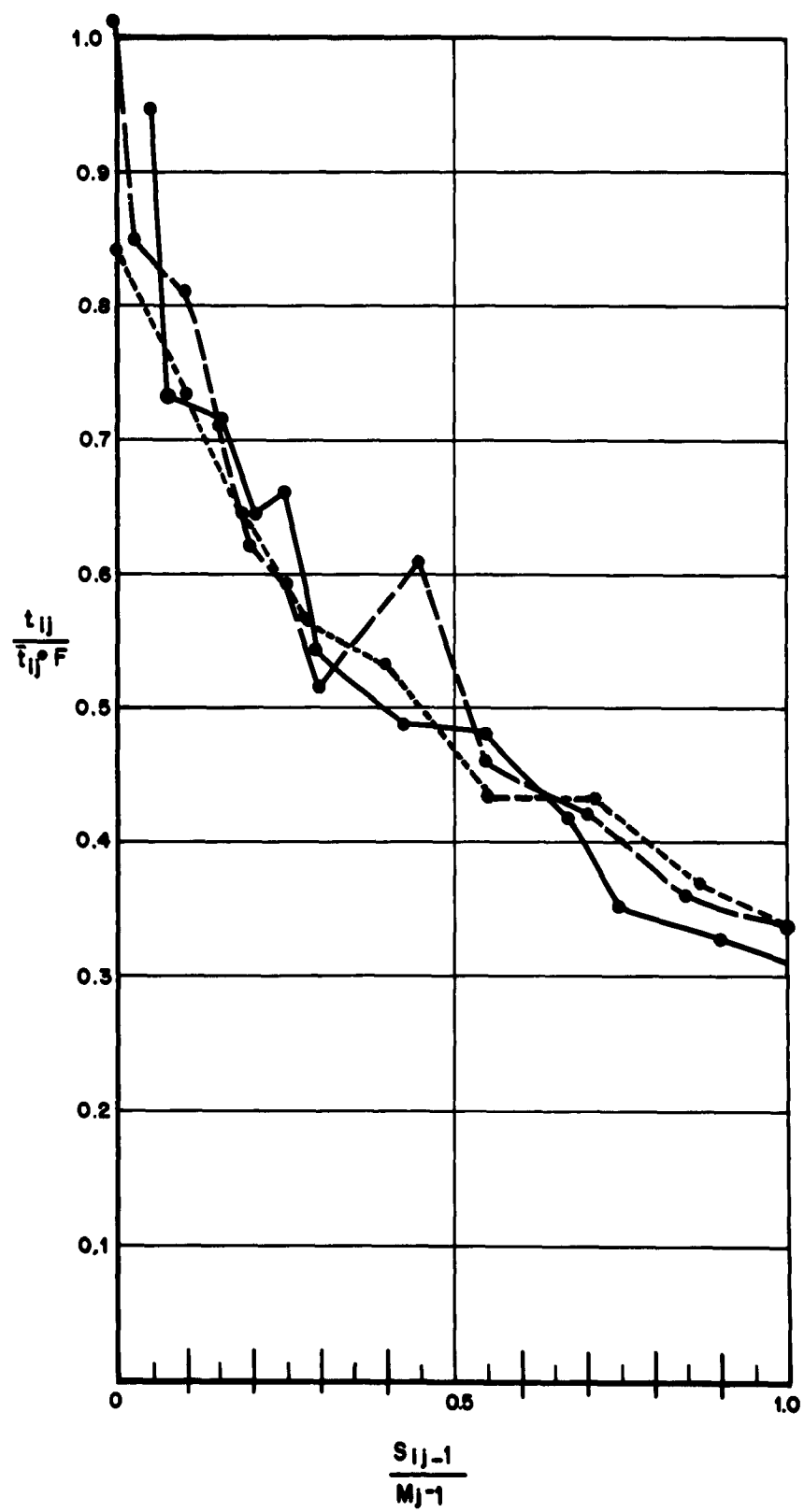
Figure 10. Normalized operator performance data.

$$\frac{t_{ij}}{\bar{t}_{ij}F_j} = Z_{ij} = -1.8290\left(\frac{S_{ij}-1}{M_j-1}\right)^3 + 3.4722\left(\frac{S_{ij}-1}{M_j-1}\right)^2 - 2.35075\left(\frac{S_{ij}-1}{M_j-1}\right) + 1.0$$

$$\text{and } 1.0 \leq S_{ij} \leq 5.0$$

then

$$t_{ij} = F_j Z_{ij} V_{ij} > 0.75$$

where $V_{ij} = \bar{t}_{ij} + K\sigma_{ij}$, as explained in Chapter II.

APPENDIX B

Calculation of Pseudo-Random Numbers and Random Deviates

CALCULATION OF PSEUDO-RANDOM NUMBERS AND RANDOM DEVIATES

The use of the model requires the sequential generation of pseudo-random numbers, uniformly distributed in the unit interval 0-1. The method selected for generation of these numbers is the power residue method described by IBM (1959). This general method as applied to the model 705 computer may be summarized as follows:

1. select any starting value of 9 digits, R_0

2. form the product $10003\ R_0$

3. the least significant 9 digits of the product is R_1

4. each successive pseudo-random number, R_{m+1}, is obtained from the 9 low order digits of the product $10003\ R_m$

By this method, a given pseudo-random number is dependent upon the preceding one and the process is acceptable only since the quantity of numbers generated by the computer before repetition is large. The method produces approximately 50,000,000 nine digit pseudo-random numbers before repetition. Employment of this method permits the exact repetition of any simulated task or subtask if the initial random number for that task or subtask is known. The exact repetition of a random process is thus facilitated by the recording of initial R_0 values for each iteration and enables detailed review of any selected simulated task.

In the calculation of t_{ij} and D^I, it is necessary to generate values of a random variable with a frequency function equivalent to that of the normal distribution (i.e., a random deviate). This was done by the direct method discussed by Box and Muller (1958) and by Muller (1959). This method gives higher accuracy than previous methods and also compares favorably with other methods in computation speed. The technique is based on the availability of two random numbers in the unit interval, R_m and R_{m+1}, taken from the same rectangular density function (see preceding section). Then X_1 and X_2

$$X_1 = (-2 \ln R_m)^{\frac{1}{2}} \cos 2\pi R_{m+1}$$

$$X_2 = (-2 \ln R_m)^{\frac{1}{2}} \sin 2\pi R_{m+1}$$

are a pair of independent random variables from the same normal distribution with a mean of zero and unit variance. This method is reported to produce normal deviates with a precision of approximately 5×10^{-7} except for probabilities less than 4×10^{-8}.